AD-414994

NAVWEPS REPORT 8062
NOTS TP 3065
COPY 6

FLOW VISUALIZATION EXPERIMENTS WITH A DOLPHIN

by

Moe William Rosen

Underwater Ordnance Department

ABSTRACT. The manner in which water flows about the body of a swimming dolphin is a subject concerning which little is known. In 1958, 2 years before the research described in this report, what appeared to be an immense transverse vortex was discovered by the author in the water spray over the back of a leaping dolphin. In addition, a peculiar system of large twin-armed transverse vortexes appeared in the spray wake behind its tail. Further original experiments that year with a fish led to the discovery by the author that a remarkable system of large discrete vortexes—the Fish Vortex System—exists in the water at the sides of a swimming fish. The resemblance of the dolphin's spray vortex to the fish vortexes in design and position was striking. These discoveries stimulated the further flow visualization research on dolphins reported here. The findings of this research indicate the presence of a vortex phenomenon under water about the body of a dolphin that resembles the Fish Vortex System.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

April 1963

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

The research reported here is part of a continuing investigation of a previously unknown fluid phenomenon discovered by the author in 1958 in independent experiments with fish and his first dolphin. The second dolphin, the Navy's Notty, was captured wild in the Pacific Ocean in 1960. She is the subject of this report.

The work was performed by the Underwater Ordnance Department and supported by the then Oceanic Research Division, Research Department, under Bureau of Naval Weapons Task Assignment R360-FR-106/216-1/R011-01-001.

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Released by
R. L. ENGEL
Senior Research Scientist
17 December 1962

Under authority of
T. E. PHIPPS, Head,
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NOTS Technical Publication 3065
NAVWEPS Report 8062

Published by . . . . Publishing Division
Technical Information Department
Collation . . . . Cover, 7 leaves, abstract cards
First printing . . . . 330 numbered copies
Security classification . . . . UNCLASSIFIED

INTRODUCTION

The manner in which water flows about the body of a swimming dolphin is a subject concerning which little is known. There has been, however, much theorizing and conjecturing in the past as to whether the nature of the flow in the boundary layer of fluid next to the skin is laminar or turbulent.

In an experiment conducted by the author in 1958,[1] what appeared to be an immense transverse vortex was discovered in the water spray over the back of a leaping dolphin.[2] In addition, a peculiar system of large twin-armed transverse vortexes appeared in the spray wake behind its tail. This was the first factual knowledge of what might be taking place in the flow about a dolphin.

Further experiments by the author reported in NOTS TP 2298 led to the discovery that a remarkable system of large discrete vortexes exists in the water at the sides of a small streamlined fish as it swims. This system, named the Fish Vortex System, had not previously been known. It possessed a strange geometry and motion and was well organized. The resemblance of the dolphin's spray vortex to the fish vortexes in design and position was striking.

These discoveries stimulated further pursuit of the flow visualization program on dolphins. The following experiments—using dyes, bubbles, particles, and the dolphin—were planned and sketched in a memorandum by the author in 1958[3] and have now been performed with the Navy's dolphin Notty. The objective of this work was to learn something about what is taking place in the water about a swimming, undulating dolphin—not only in the boundary layer, but in the entire fluid field surrounding the animal. This was a formidable task, considering that the animal is a strong heavy creature, nearly 7 feet long, with a mind of its own, rather than an inanimate test model that will stay where placed in a water or wind tunnel and allow investigation at will by established methods.

Philosophically, these experiments were intended to observe whatever facts nature would present and to make only such conclusions as could be based on these facts.

[1] This experiment was made with a dolphin other than Notty, the dolphin used in the Navy's work in 1960–61.

[2] U. S. Naval Ordnance Test Station. Water Flow About Swimming Fish. China Lake, Calif., NOTS, May 1959. 96 pp. (NOTS TP 2298.)

[3] Several Methods for Visualizing Water Flow About a Swimming Fish (and Dolphins). 7 August 1958.

DYE EXPERIMENTS

The dolphin and the experimenters (the writer and the trainer, Ralph Penner) worked together as a team at Marineland, California, for many weeks so that the acts necessary for the dye experiments could be thoroughly learned. The dolphin was trained to stop in front of the experimenters and to allow the dye to be smeared by hand on her skin as she raised her head out of the water. This act had to be performed with swiftness and surety so that a controlled and uniform dye patch of known size and location could be put on the restless creature. She was trained to swim, on signal, between the wall of the 30-foot-diameter basin and a row of posts arranged under water parallel to the wall and 3 to 4 feet distant. The final experiments were performed at Convair in San Diego, California, in a 300-foot-long, 12-foot-wide straight concrete channel containing a 6-foot depth of sea water.

As the dolphin swam in the long channel, the dye dissolved, leaving a stream of colored water that could be observed.[4] A large black background with white grid lines marking 1- by 1-foot squares was fixed flush to the wall and served both as a color contrast and as a geometric backdrop. A camera, placed at an underwater window opposite the grid, viewed the dolphin as she swam past. The experiments were hampered, however, by murky water caused by the growth of minute sea life—flagellates and algae.

Each dye patch was centered at the top of the dolphin's head and was roughly 6 inches in girth, 4 inches in fore-and-aft dimension, and generally not over 0.02 inch thick. At the edges, the dye patch rapidly became thinner because of the action of the water remaining on the dolphin's wet skin.

When lights were used to illuminate the camera's field of view, the dolphin sometimes swam on the outer side of the posts to avoid the bright region. Thus, not all tests were successful.

The following describes some examples of the visible features of the flow, as shown by these dye experiments.

Dye Patch on Head, Undulating Swimming

The photographs of the dye experiments were not perfectly clear because of the murky water caused by minute sea life. Nevertheless, they show features of scientific value.

In a good run, the dolphin swam on her prescribed course between the posts and the grid after a carefully controlled and very thin patch of dye had been placed on her head with the leading edge of the patch just aft of the animal's blowhole (Fig. 1). The purpose of this experi-

[4] The first dye experiment with live dolphins was made by the author in early 1958 on some show dolphins. These animals would dart off in an unpredictable direction before a good patch could be applied. Nevertheless, certain features of the trail were momentarily visible.

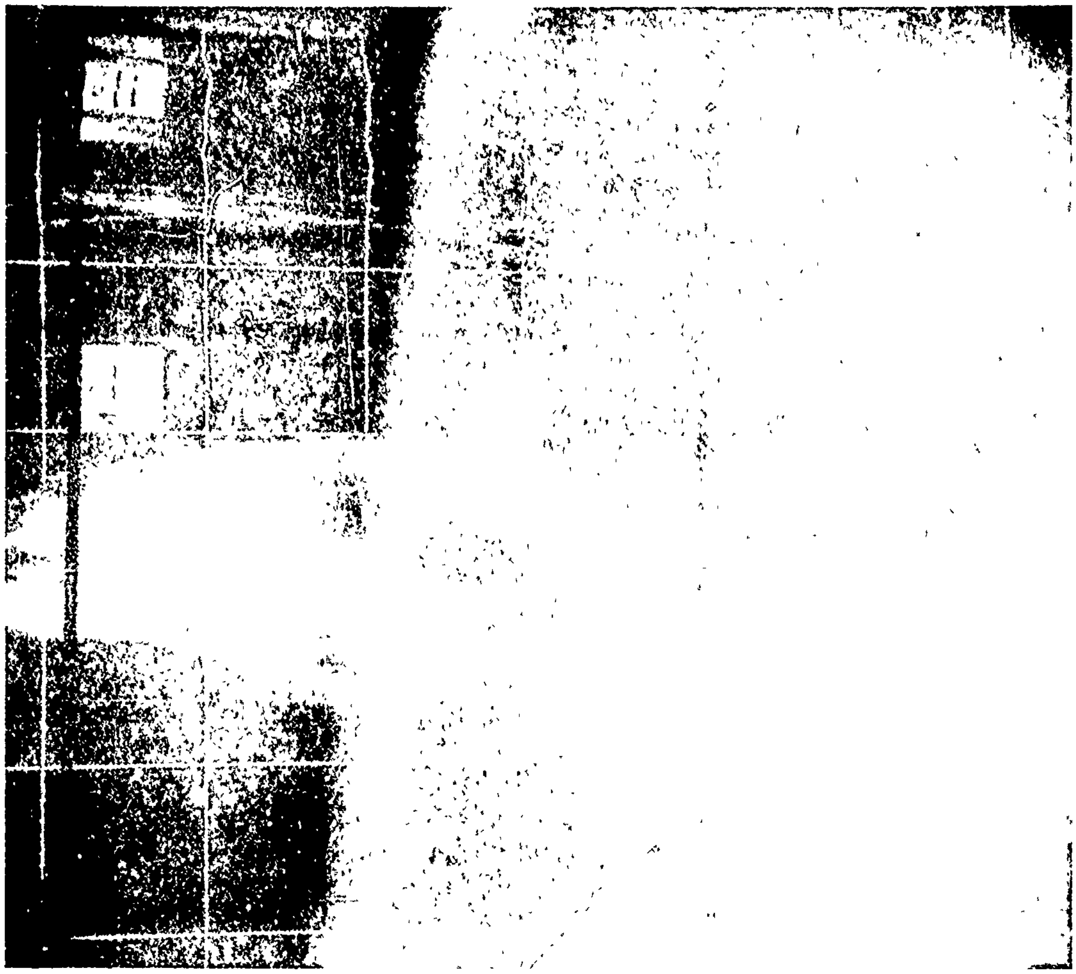

FIG. 1. Dye Flow Streamer Made by Undulating Dolphin Swimming Between Grid Background and Poles. The peduncle and the tail are seen at the end of their downstroke, somewhat blurred by their rapid motion.

ment was to observe the flow as the dolphin swam in a natural state with a definite amount of undulation as she passed through the field of view of the camera.

The streamer may be seen flowing back from the head along the skin. It passes the dorsal fin and continues behind it on the upper rear surface. At first the band of dyed water appears reasonably (but not perfectly) uniform in its flow. However, changes begin to take place, the flow definitely becomes less smooth. Well before the streamer reaches the dorsal fin base, its uniformity is gone and it takes on a somewhat rougher appearance. At this point it would be unwise to

make any definite conclusions as to the exact state of this flow, but it can be seen to undergo a gradual change along the dolphin's body. Aft of the dorsal fin the band becomes considerably more diffused and appears eventually to disperse itself. The peduncle and the tail may be seen at the end of their downstroke, somewhat blurred by their rapid motion.

A moment later the tail is apparently traversing the middle of the dye stream, which is seen aft of the tail in a thin arc, reasonably well defined (Fig. 2). It is apparent that this trail is not straight in its form. The shape of the trail is that of a series of connected waves that do not appear sinusoidal in shape. This series of wave forms is in keeping with the appearance of the wave trail originally discovered in the wake of a small fish and reported in NOTS TP 2298. The wave trails of dolphins and fish are similar despite their great difference in size.

FIG. 2. Dolphin's Tail, at Left, and Dye Streamer. Photograph taken a moment after Fig. 1.

FIG. 3. Dye Trail Left by Dolphin. Notice increased diffusion of stream.

Figure 3 was taken a fraction of a second after the dolphin had passed. The stream is still reasonably well defined except that the upper part of the lobe seems to be in a more diffused state than it was the previous moment (Fig. 2). The major portion of the stream seems to have maintained its identity.

The trails left by the dolphin in these dye experiments did not always have the same over-all shape or texture. In one run, the usual amount of dye was placed in the same way and at the same location on the dolphin's head, but some variations in the flow were found. Figure 4 illustrates one such difference when the trail seen there is compared with the trail in Fig. 3. Figure 4 was also taken a moment after the passage of the dolphin, and an arc can be seen that is about the same size as the one in Fig. 3. There are two differences, however.

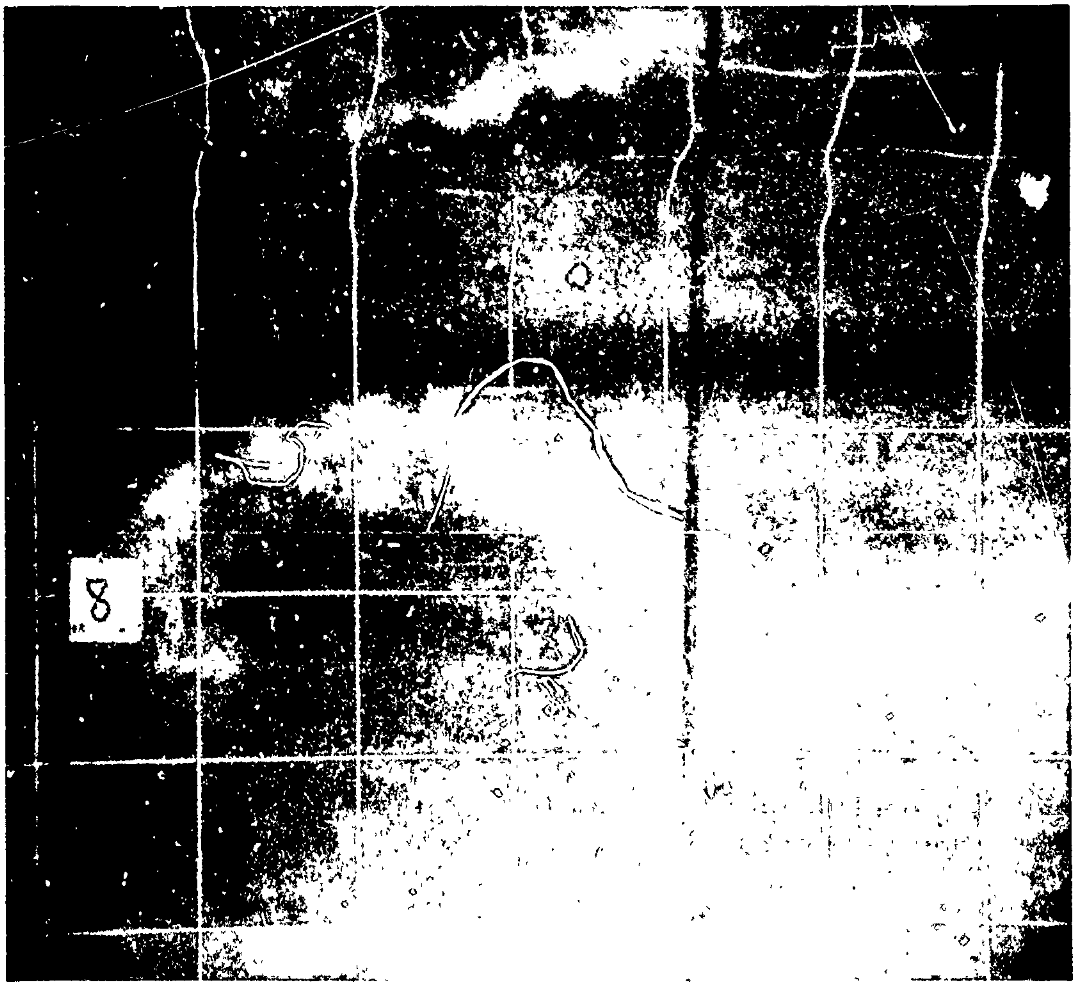

FIG. 4. Discontinuous Wave Form in Dye Trail Left by Dolphin. Photograph taken a moment after Fig. 3.

The wave form in Fig. 4 is discontinuous, with a joint appearing at the place where the arc joins a straighter section at the right. The trail in Fig. 3 is a continuous arc with no visible joint. The texture of the trail in Fig. 4 is puffier than the smooth streamer in Fig. 3. A hook may be seen in the left end of the trail in Fig. 4 that is not present in Fig. 3.

Flow Similarity

The differences in the appearance of the streamers indicate that the dolphin does not necessarily swim in exactly the same manner on each run. This may be attributed to a number of reasons. One is, perhaps, that because the animal's body is flexible, it can assume an almost

unlimited number of shapes determined by its anatomy. Even though from outward appearances the dolphin may seem to be moving in the same manner as previously, its exact flexure may be different in subtle, almost undetectable, ways. This may be a slight difference in the angle of attack of the forward body as the dolphin prepares to gain speed, turn, slow down, gain depth, or rise. It is impossible to state with assurance that it behaves identically in several runs or even along the course of one run: it is not a machine that repeats its motions exactly. Consequently, the fact that there may not be exact "flow similarity" when comparing several runs that otherwise may appear identical must be taken into consideration. It would reasonably follow then that the geometry of the flow, and perhaps also the intrinsic character of the flow, would change; this might become evident in the trailing stream. These experiments present evidence that such changes do take place.

BUBBLE EXPERIMENTS

It was thought that air bubbles released in the water and floating upward would reveal the water motion. A bubble machine was constructed, which released a 9-foot-long screen of bubbles. The main element was a tube of surgical rubber with tiny punctures every 2 inches. Air under regulated pressure was forced into the tube and pulsed through the punctures. The tube lay at the bottom of the channel, and it was found that the machine made its bubbles very satisfactorily. Bubble size could be controlled from about 0.01 to about 0.12 inch in diameter.

The dolphin, after a period of familiarization, swam through the bubbles, provided they were kept small. However, this method did not give the desired results because of practical and compelling reasons stemming from the rate of rise of the bubbles. To show a true flow vector, the bubble must be quite small—not larger than about 0.02 inch. The rate of rise is then low enough so that the bubbles will follow approximately the flow lines of the water.

When these small slow-rising bubbles were tried, it was found that the camera could not see them through as little as 4 or 5 feet of sea water despite many different arrangements of powerful lights. The only bubbles that could be seen at 4 or more feet were those 0.08 to 0.12 inch in diameter. However, these would rise very rapidly (at the rate of approximately 1 to 1 1/2 feet per second) with a spiraling unstable motion. It quickly became obvious that this could not show the flow. When the camera was placed close enough to see the small, slow-rising bubbles, its field of view became so limited as to be of no practical use. Therefore, although the bubble machine operated well, the bubbles themselves did not. This phase of the experiments was discontinued. Instead, the particle experiments were started, which on both a theoretical and practical basis had considerably greater merit.

PARTICLE EXPERIMENTS

The particle experiments were designed to detect the motion of the water in the field about the dolphin.

A two-dimensional screen or curtain of large particles was created underwater with the aid of gravity. The plastic particles had a density slightly greater than that of sea water. The particles emerged slowly from a long special trough, drifted down at a rate of about 1/8 inch per second, and created a rough plane nearly 10 feet long, 6 feet deep. Its plane was parallel to the channel walls and lay between the posts and the grid. The premise was that as the dolphin swam through this curtain in the direction of its plane, the motion of the particles would be that of the water.

The generation of this curtain was the result of a considerable number of preparatory experiments in Morris Dam Lake in an attempt to find a way of creating a visible, underwater picture over a large field of the water's true motion.

It was necessary for the water to be practically motionless before the arrival of the dolphin. A large solid metal barrier with a sliding gate was designed and installed to confine the dolphin. Two roll-up canvases were held taut by heavy bars to calm stray underwater currents. The method worked well, and the water became very quiet. The fragile underwater particle curtain was generated with success. The dolphin was released through the barrier's sliding gate, and on signal swam down the channel between the posts and grid where the curtain was suspended.

The murky water again produced difficulties. Also, at times, the animal would be reluctant to swim the course set for her in this experiment. She had worked for many days in the small, round tank at Marineland and had become accustomed to swimming through clouds of these particles. In the small tank, it was not possible to duplicate the curtain formation or the actual physical arrangement required for the experiment. At the final site—the large straight basin—there was no opportunity to train and accustom her to the actual situation. Consequently, the dolphin swam slowly and warily, usually sliding to the side of the brightly illuminated particles. It was not possible to tell with certainty on any particular trial whether or not she had actually gone through the curtain, but on the two runs illustrated, it is known that she did go through.

Figure 5 is a photograph taken at high speed showing one such underwater scene. A casual glance reveals nothing unusual, but a careful inspection shows that the white particles ahead of the dolphin's nose appear as short streaks because they are moving.

An interesting and revealing picture in another run was made with a short time exposure, when the camera shutter remained open for a fraction of a second (Fig. 6). The dolphin is blurred into the back-

FIG. 5. Dolphin Swimming Among Particles. Streaks in front of dolphin's nose actually are moving particles.

ground and cannot be seen, but the particle motion is at once detected. The dolphin moved from right to left, and the motion of the particles is seen as streaks.

Most certainly the motion of the particles is not random. It appears that the particles have paths that are portions of an organized pattern, which evidently is larger than the camera's 8-foot-wide field of view.

In the lower half of the photograph, the particles appear to be radiating on inclined paths. In the upper left portion, the particles are moving in short hooked paths, and their general direction is more horizontal than the direction of the particles below.

If the particles in Fig. 5—the photograph taken at high speed—are examined closely, the following is observed. The particles as far as 3 feet above the animal and forward of her nose are moving horizontally. The particles below her body and forward of her nose are moving along inclined paths. Thus, there is a correspondence between the particle

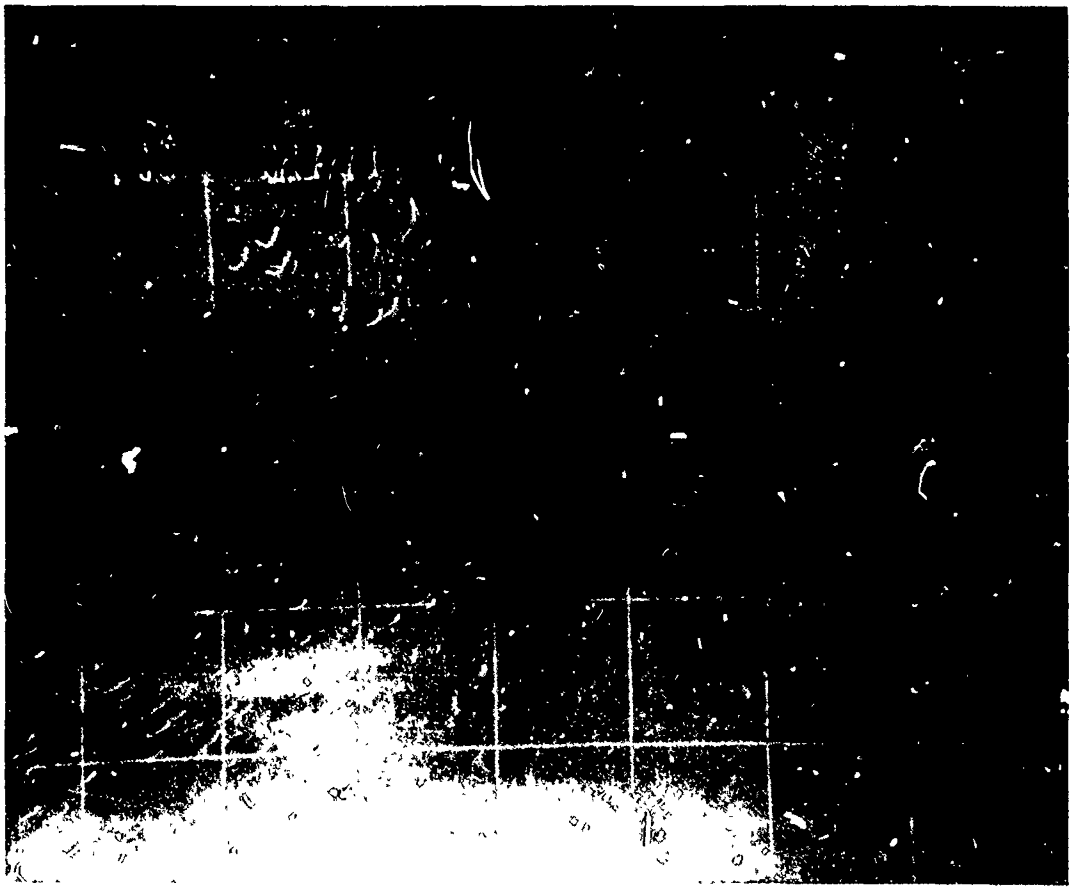

FIG. 6. Particle Flow Pattern Made by Swimming Dolphin.

motions seen in Fig. 5 and those seen in Fig. 6, although the photographs are of different runs.

It can be seen from the foregoing data that the water is engaged in an organized flow. No homogeneity exists in the water's motion along the axis of the animal's path, nor along a direction normal to its path. These are the characteristics of pattern rather than of uniformity.

At this point, it would be well to refer to the system of flow reported in NOTS TP 2298. In the experiments cited there, the water motion caused by a live fish was, for the first time, made visible. It was discovered that as the fish swam in a normal uninhibited manner, it generated a strange system of flow about its body. With each stroke of its tail, a discrete unified disturbance appeared at the sides of the animal. These disturbances were found to be masses of spinning water—vortexes.

As the fish swam, each vortex underwent an evolutionary process. When the fish passed, each vortex developed spiral arms, which, in

unwinding, linked themselves in a trail. The trail resembled a wave series and at first was mistaken for a "Karman vortex street"—a system of disturbances left in the wake of blunt bodies moving through fluids. However, it was found not to be such a "street" and, moreover, existed at the sides of the fish, not merely in its wake.

The existence of such a vortex system at the sides of a fish had not been known or even suspected previously. This system was unlike the conventional concept of parallel streamlined flow about a fish.

The tracks of the particles shown in Fig. 5 and 6 can be interpreted as showing the water flowing down and to the left in curvilinear or arced paths. This is especially noticeable in Fig. 6 and could indicate a vortex.

The third particle trial resulted in a similar but more complex pattern, as displayed in Fig. 7. The particles are moving in what seems to be a stream flowing down and splitting in two directions, left and

FIG. 7. Complex Flow Pattern Made by Swimming Dolphin. Two circulatory systems are evident.

right, again in arced paths. Another interpretation is that two circulatory systems, namely vortexes, are being observed. Also observed are the conditions in the region where the two vortex flows are divergent. The latter interpretation, when considered in conjunction with the track curvatures presented by Fig. 6, seems to be more meaningful and more representative of what actually may be happening.

The significance of these experiments lies mainly in these evidences: The shape of the dolphin's streamer in the dye experiments closely resembles the wave-like trail generated by the fish in the experiments reported in NOTS TP 2298. In addition, the flow of the water significantly takes on a pattern of organized geometry, which seems to be similar to the strange water motion originally discovered in the experiments reported in NOTS TP 2298—a vortex system. The water's motion in the field about the dolphin seems not to be the well known straightforward flow, which is familiarly envisaged as occurring in the characteristic manner over standard three-dimensional forms. The system evidently is complex, yet at the same time possesses order.

Whether this organization, as evidenced by the presence of the vortexes, is identical in all respects to that of the fish is not definitely known. Nevertheless, the resemblances of the flow about the dolphin to the phenomena discovered in the experiments reported in NOTS TP 2298 are most marked and are evidence supporting the reality of the flow phenomena observed about the fish in those experiments.

One of the important conclusions drawn from the fish experiments was that because the flow geometry discovered was not in conformance with known flows, standard hydrodynamic methods of computation could not be applied with complete validity. Terms such as "thrust" and "drag" could not have the same meaning in a discussion about a swimming fish as they do in a discussion about a man-made vehicle. In the latter case, a propeller provides all the thrust, and a rigid body must be pushed through the fluid and supplies all the resistance. The fish experiments showed no clear separation of drag and thrust. Thus, it was reasoned that the normal mathematical treatments based on rigid bodies and the definitely separated functions of thrust and drag could not strictly apply.

As the flow visualization experiments with the dolphin described here show some similarities to the flow originally discovered in experiments and reported in NOTS TP 2298, the premises stated there might also logically apply to the swimming of a dolphin.

ACKNOWLEDGMENT

The writer is indebted to Ralph Penner of Marineland, California, trainer of Notty, and to Earl Blake of Morris Dam. These men, the author, and the dolphin performed the actual experiments. Mr. Blake and Robert Graf, also of Morris Dam, constructed the odd apparatus necessary for the work.

Gratitude is extended to Dr. René Engel of the Research Department for his support and for making this project possible.

Last, but not least, thanks are extended to Notty.

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ABSTRACT. The manner in which water flows about the body of a swimming dolphin is a subject concerning which little is known. In 1958, 2 years before the research described in this report, what appeared to be an immense transverse vortex was discovered by the author in the water spray over the back of a leaping dolphin. In addition, a peculiar system of large

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